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A Selected Review of Hydrodynamic Force Coefficient Data on Stranded Wires Used in Fishing Gear

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2570 Dole Street
Honolulu, Hawaii

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Scottish Fisheries Research
Report Number 31 1984
ISSN 0308 8022

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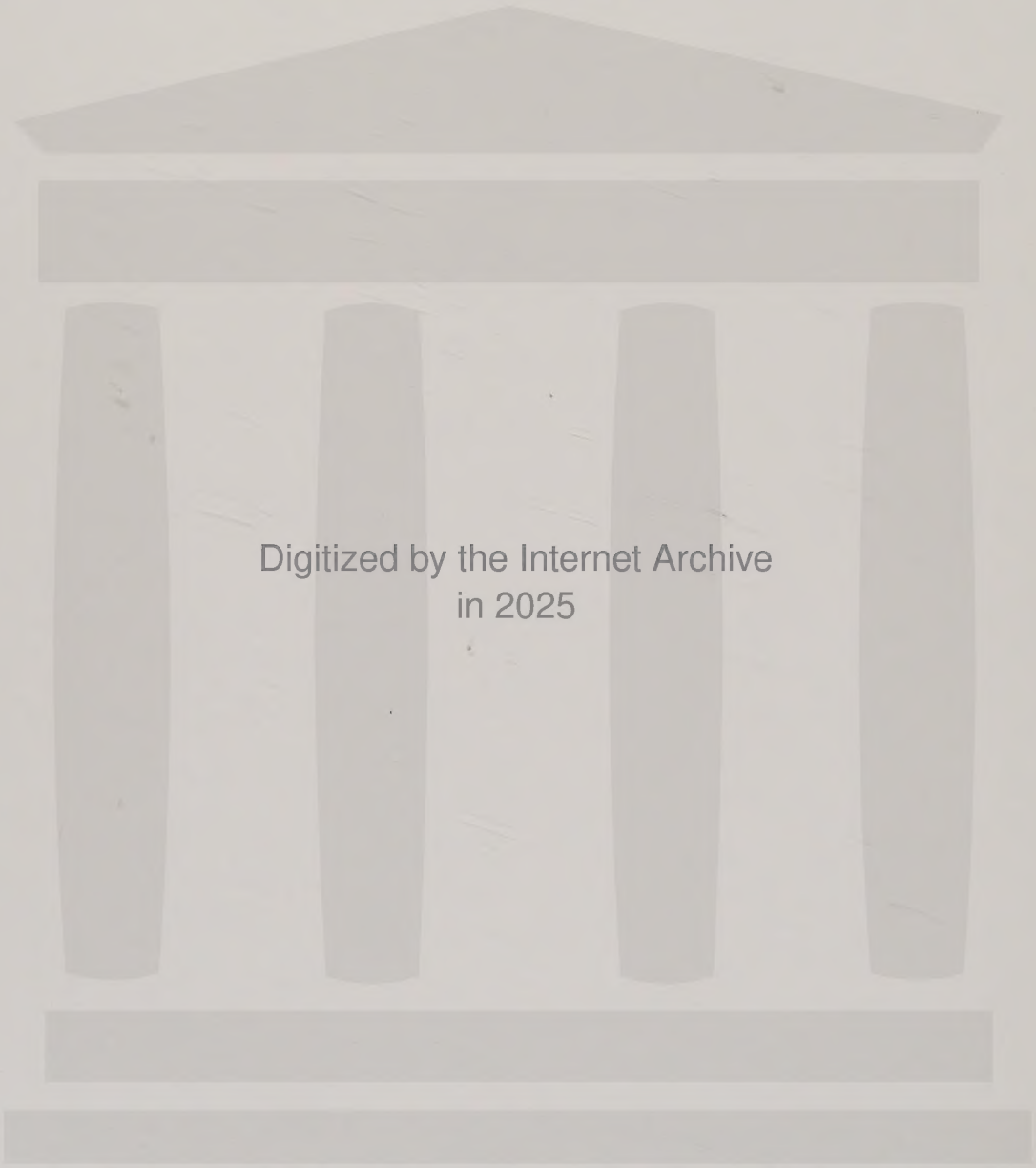

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A Selected Review of Hydrodynamic Force Coefficient Data on Stranded Wires Used in Fishing Gear

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Introduction

Stranded wire or rope is used in the construction of almost all types of fishing gear and its behaviour can be a significant factor in the effectiveness of the catching process. Wires are used in trawls and seine net gears to herd the fish into the path of the net. The wire shape affects not only the behavioural response of the fish but also the effectiveness with which the net is spread. With the introduction of pelagic trawls towed at high speed in deep water and of two boat trawls with very long warps and sweeps the calculation of wire behaviour assumes greater importance in the prediction of the engineering performance of trawls.

In the 1950s and early 1960s fishery scientists considered the determination of wire shape as a static three-dimensional problem. They tried to find simplified solutions mathematically, considering gravity and one or two components of hydrodynamic force acting on the wire. The application of computing methods allowed quicker and more accurate solutions. The accuracy of prediction of shape depends on the validity of the assumptions about the hydrodynamic forces. In order to provide values for the hydrodynamic forces acting upon the warp, experiments have been made in the laboratory (tank, wind tunnel) and at sea.

The aim of this paper is to compare the values of hydrodynamic force coefficients obtained from measurements and to suggest values for practical use in computer programs for the calculation of stranded wire shape.

All the examples and discussion in this paper consider trawl warps between the ship and the trawl (Fig. 1) but the principles may be applied to any wire or rope with twisted strands used in any type of fishing gear.

Basic Definitions and Equations

Basic equations in terms of x, y and z components

Consider the equilibrium of the warp (Fig. 2). The axis system has the z-axis downwards, the x-axis in the direction of the water velocity relative to the wire and the y-axis perpendicular to the x-z plane. The origin is located at the sea surface at the forward end. Throughout this paper the velocity is that of the water relative to the wire.

A small element of the wire has length ds and makes angles α, β and γ to the x, y and z axes respectively.

The tensions at the ends of the element are T and T+dT and the resultant external force (due to weight and hydrodynamic forces) is r per unit length. The equation of equilibrium is then

$$dT + rds = 0 \qquad (1)$$

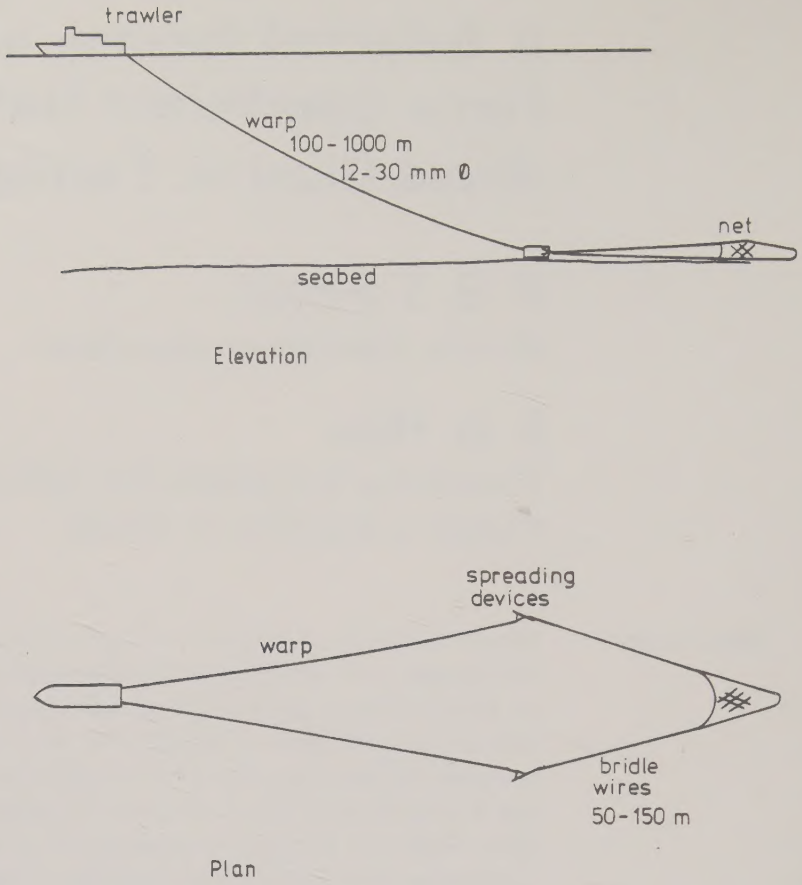
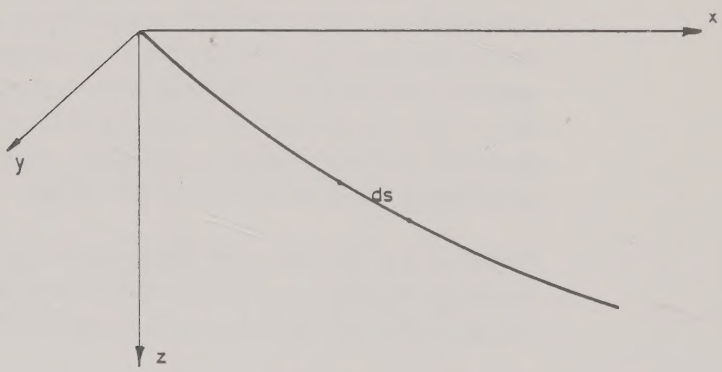


Figure 1. The elevation and plan of a trawl gear showing the principal components.



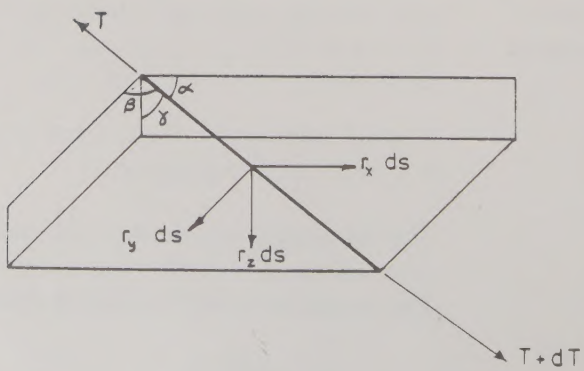


Figure 2. The warp axis system with force and angle conventions.

External force components

The components of the external forces acting on each element have physical meaning when they are referred to axes relative to the element. There are considered to be four components $r_n ds$, $r_t ds$, $r_s ds$ and wds as shown in Figure 3, where

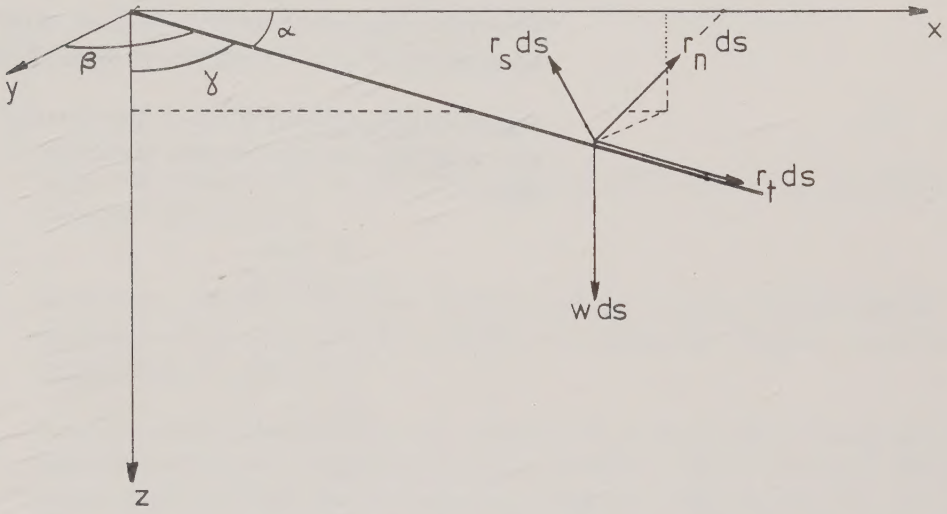
$r_n ds$ is the normal force lying in the plane containing the element ds and the velocity, and which is perpendicular to the element ds

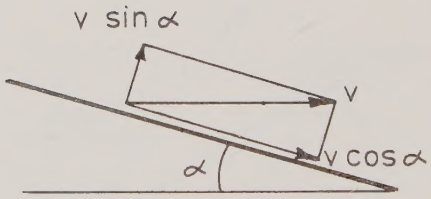
$r_t ds$ is the tangential force acting along the element ds

$r_s ds$ is the side force perpendicular to the plane containing r_n and r_t

wds is the weight of the element in water

The form of each component will be discussed in turn





View in the plane of the wire element and

v, the water velocity relative to the wire

Figure 3. The forces acting on a wire element with reference to the element axis system

According to the crossflow principle, when the element is inclined at an angle α to the flow, the tangential component of velocity is assumed to have negligible effect on the pressure distribution round the section of the wire, so that the normal force will result only from the normal velocity components. Since the pressure acts normal to the element and is proportional to velocity squared the formula for r_n, the force per unit length, can be written as

$$r_n = C_n \tfrac{1}{2} \rho v^2 \sin^2\alpha \, d \qquad (2)$$

The direction of the normal velocity component v sin α is defined as the positive direction of r_n (see Fig. 3).

The value of the tangential force per unit length r_t is small and is considered to be due mainly to friction. It is defined as

$$r_t = C_t \tfrac{1}{2} \rho v^2 d \qquad (3)$$

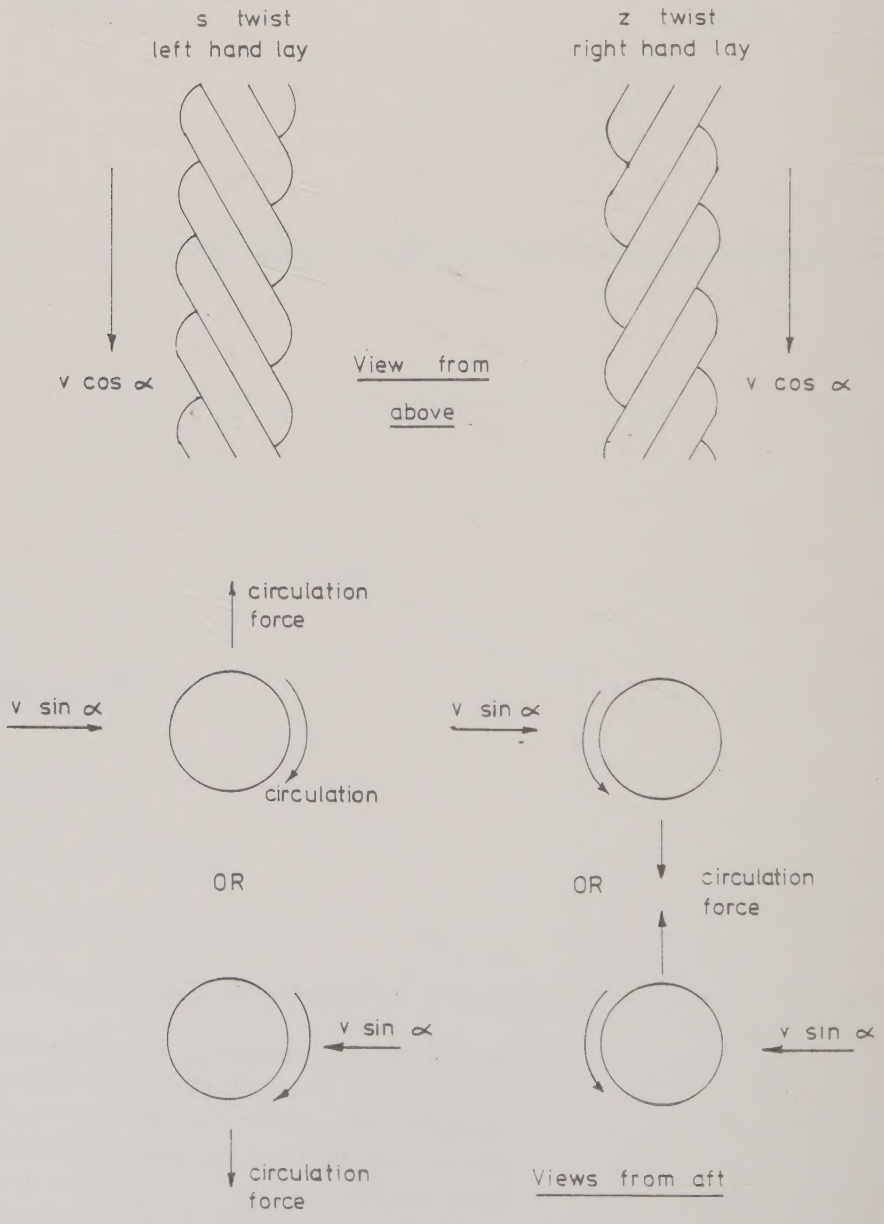
where the direction of v cos α is defined as the positive direction of r_t.

The side force per unit length, r_s, is caused by the circulation round the wire due to the stranding or lay of the wire. It is defined as

$$r_s = C_s \tfrac{1}{2} \rho v^2 d \qquad (4)$$

where the positive direction is defined as downwards; that is, when the z component of r_s is in the positive z-axis direction then r_s is said to be positive.

Figure 4 shows the direction of the circulation force relative to the circulation direction and the velocity component v sin α of the water relative to the wire.



Note that the velocities are shown as water velocities relative to the wire.

Figure 4. The direction of the circulation force caused by the stranded construction of the wire

The direction cosines of r_n, r_t and r_s are, respectively,

$$(\sin\alpha, -\cos\alpha\cos\beta/\sin\alpha, -\cos\alpha\cos\gamma/\sin\alpha),$$
$$(\cos\alpha, \cos\beta, \cos\gamma)$$

and

$$(0, -\cos\gamma/\sin\alpha, \cos\beta/\sin\alpha)$$

Thus the components for r in the x, y and z directions are

$$r_x = C_t\, k\cos\alpha + C_n\, k\sin^3\alpha$$
$$ry = C_t\, k\cos\beta - C_n\, k\cos\beta\sin\alpha\cos\alpha - C_s\, k\cos\gamma\operatorname{cosec}\alpha$$
$$r_z = C_t\, k\cos\gamma - C_n\, k\cos\gamma\sin\alpha\cos\alpha + C_s\, k\cos\beta\operatorname{cosec}\alpha + w$$

where

$$k = \tfrac{1}{2}\rho v^2 d \text{ and } C_n = C_n'/\sin^2\alpha \qquad (5)$$

These expressions may be used with equation (1) to determine the change in tension along a wire.

Data on Force Coefficients

Measurement methods

Wires and cylinders inclined to the flow have been tested in experimental facilities such as wind tunnels or flume tanks using short lengths, as well as at sea using real trawl wire.

In wind tunnels it is convenient to measure the hydrodynamic forces parallel and perpendicular to the speed direction, in the x, y and z directions. Some investigators also use other axis systems. However, the physical basis of the relationships between angles and force coefficients is better understood with respect to axes normal and tangential to the wire. For ease of comparison we have converted all data to the axis system normal and tangential to the wires (see Fig. 5 for the two dimensional case).

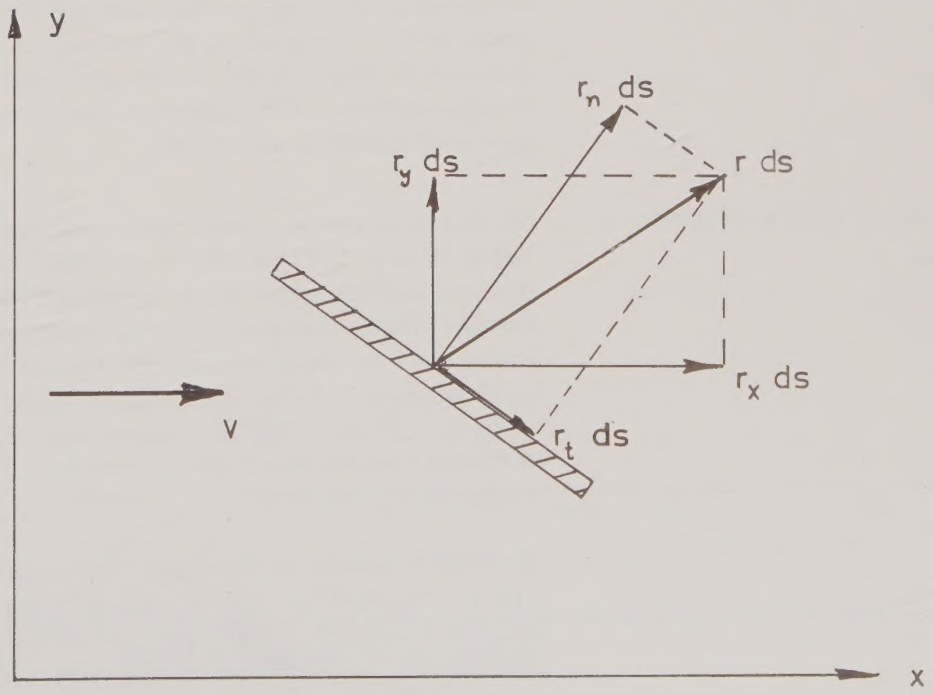


Figure 5. The relationship between the x and y components and the normal and tangential components of the forces acting on a wire element in two dimensions.

It should be noted that when data have been obtained from other references, values have been taken from mean lines through the experimental points and then corrected to the n, t, s axis system. Thus the values are not necessarily experimental points.

The greatest uncertainty in wind tunnel or tank experiments lies in reproducing the real conditions in which the wires are used. The use of large models of warps aims to improve the accuracy of the force measurements. Stengel (1968) used models of 8 times full-scale diameter with an aspect ratio of 12; the individual filaments on each of the 6 strands were not twisted but lay parallel to the axis of each strand. Stengel found discrepancies between model and full-scale measurements which required the use of a correction factor to achieve similarity.

Relf and Powell (1917) applied an end correction of four diameters to their results at all angles.

Measurements have been made at sea (Alekseev, 1964; MacLennan, 1979) by towing a trawl warp at various speeds with no load at its lower end. In steady motion with no differential tide or current the warp will lie at a constant angle, the critical angle, to the water surface along its whole length. By measuring the load and the wire angle at the ship the normal and tangential coefficients can be determined. The main problem with this method is that the towing speed determines the wire angle and it is not possible to separate the effect on the coefficients of the two parameters. Moreover, the data are difficult to interpret because the Reynolds Number (which is in the critical region between 10^4 and 5×10^5) is not constant. Starovoitov (1975) developed a method which might be used to overcome the Reynolds Number (R_d) problem, by measuring the drag of a wire with a weight on the lower end. This has the disadvantage that the wire may be significantly curved and only a short length can be considered, therefore.

Data from sea trials are often scattered because of the difficulty of measuring the tension and angle. It should be noted that when the angle is measured by a pendulum declinometer that is located close to a vibration node or the towing point, the instrument is subjected to angular accelerations which may bias the results significantly (MacLennan, personal communication). It is not known how much error in MacLennan's results was contributed by this effect.

Normal force coefficient, C_n

Much data exists on normal force coefficients of smooth and stranded cables (Every, 1981; Griffin *et al.*, 1982). In the fishing technology field Nomura and Nozawa (1955), Matrosov (1961), Chubarov (1962) and Stengel (1968) have also provided data. Some of the considerable range of values given by these workers may be due to Reynolds Number effects or to differences in model construction (aspect ratio, strand size, coefficient of twist, etc). It should also be borne in mind that the measurement accuracy may be low at low α because of the relatively small forces and angles being measured.

Another influence on the normal force coefficient is vibration. Skop *et al.* (1976) proposed methods of predicting the drag coefficient of a vibrating cable as a function of amplitude and of natural and vortex shedding frequencies. Further experimental work is required to provide empirical formulae for the prediction of vibration amplitude.

Crewe (1964) developed a theory which suggested that drag coefficients should be increased by a factor of up to four at resonant frequencies.

Wires tested in wind tunnels or tanks may be subject to unrealistic or negligible vibration but a representative value for the normal force coefficient at $\alpha = 90^{o}$ is $C_n 90 = 1.1$

Limited full-scale trials have been undertaken at sea by Alekseev (1964), Starovoitov and Nikeshin (1975) and MacLennan (1979, 1980).

Using a 26.4 mm warp Alekseev (1964) obtained data over a range of attack angles from 9^{o} to 20^{o}, corresponding to a speed range from 5.9 to 2.8 m/s.

Starovoitov and Nikeshin (1975) experimented with a 23.5 mm diameter warp over a wider range of attack angle from 15^{o} to 45^{o}, corresponding to speeds from 3 to 1.1 m/s.

MacLennan (1979, 1980) used wires of diameter 24.1 and 15.4 mm at angles from 15^{o} to 40^{o}, corresponding to speeds from 3 to 1 m/s.

Figure 6 shows the variation of C_n and C_n' with α. Because the variation in attack angle was achieved by changing towing speed, the Reynolds Number is not constant (coefficients are plotted against speed in Fig. 7). However, this is unlikely to explain completely the rather high values of C_n over 1.2.

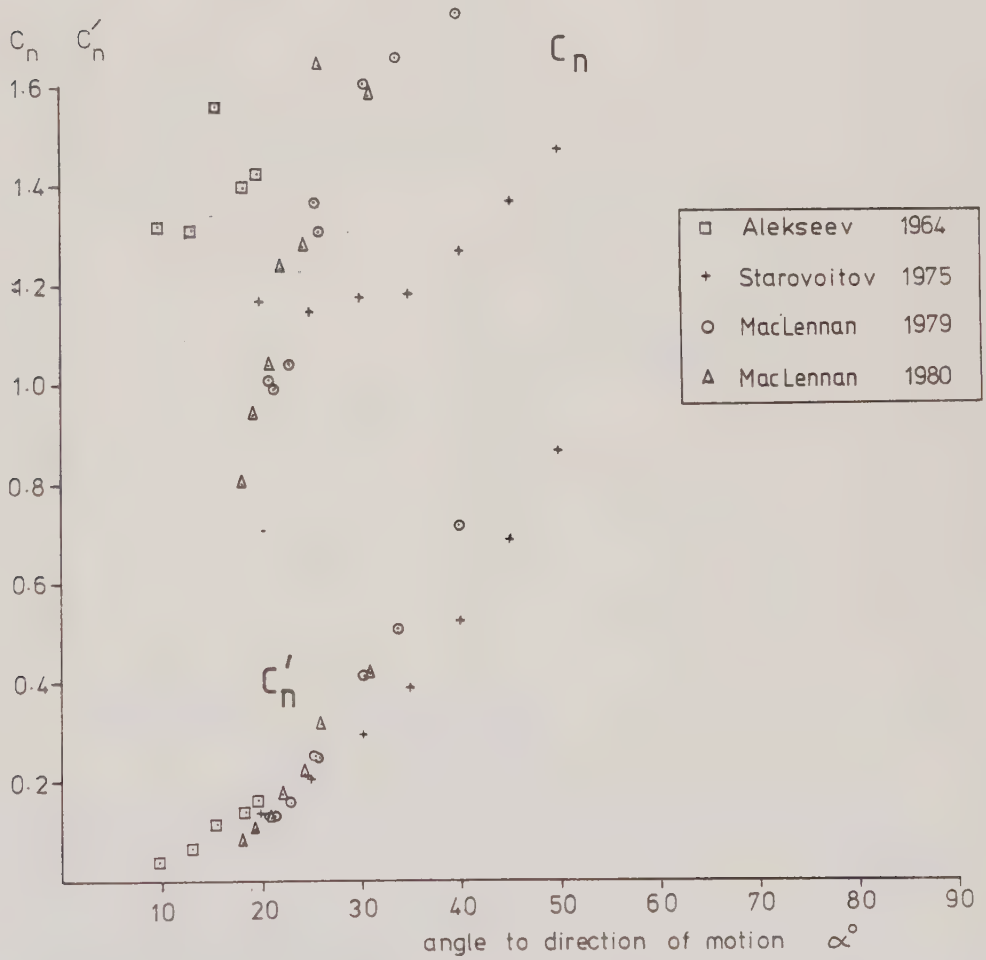


Figure 6. The variation of normal force coefficients for stranded wires with angle to the direction of motion, from sea trials data

In these experiments the wire tension is low compared to that occurring during trawling. In general, the natural resonant frequency will increase with tension while the forcing frequency caused by vortex generation will increase with speed. Maximum resonance occurs when the two frequencies coincide but the natural frequency is very much lower than the forcing

frequency. However, for a streamed warp with only a weight at the end the tension increases as the speed reduces so that in this case the two frequencies would approach significantly closer to the maximum resonance condition. The data of both MacLennan (op. cit.) and Starovoitov and Nikeshin (op. cit.) show a large increase in C_n as speed is reduced (Fig. 7) corresponding to vibration factors on C_n in the range 1.0 to 2.0. It is tentatively suggested that this is due to rapid changes in the vibration characteristics with speed.

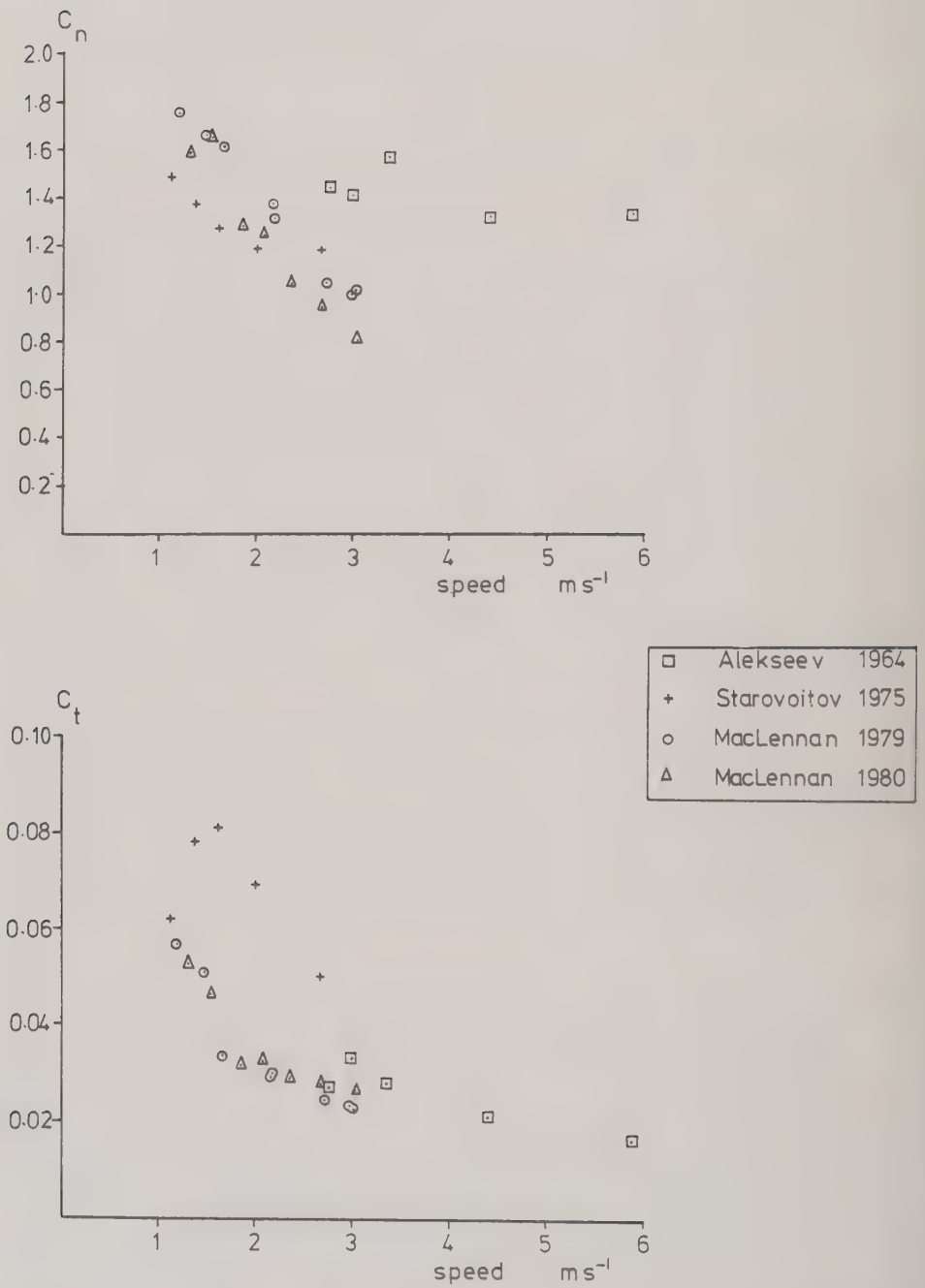


Figure 7. The variation of normal and tangential force coefficients for stranded wires with speed, from sea trials data

These data suggest that vibration has a major effect on the normal force coefficient, and that the practice of testing streamed wires may produce values of normal force coefficient which are not representative of trawling conditions where the tensions are considerably higher.

It should be noted that MacLennan's analysis considered only the two dimensional case with no side force; his data have been reworked assuming the variation of C_s proposed below (p. 17) to obtain values for C_n and C_t.

C_n may also depend on the number of strands. In Figure 8 data for 3, 6, 18 and 20 strand wire are plotted (Chubarov, 1962) against α. There is some indication at angles of attack over 50° that C_n and C_n' depend on the number of strands. The reduction in C_n at $\alpha = 90°$ as the number of strands is reduced may be explained partly by the reduction in effective hydrodynamic thickness of the wire as the number of strands is reduced (Ferro, 1981).

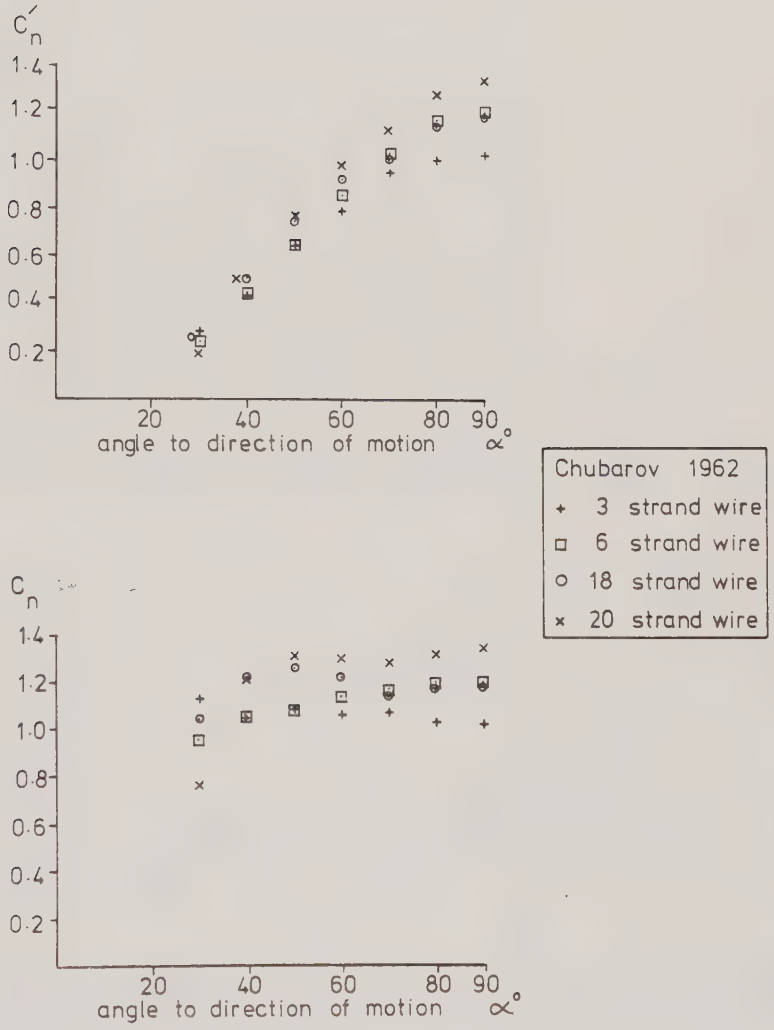


Figure 8. The variation of normal force coefficients with angle to the direction of motion for wires with different numbers of strands round the circumference

Tangential force coefficient C_t

The tangential force is small and difficult to measure accurately. The experimental evidence is scattered.

Hoerner (1965) compared the experimental results for inclined circular cylinders from various sources and quotes formulae for C_x and C_y.

These formulae may be combined to give

$$C_n' = C_{n90} \sin^2\alpha + \pi C_f \sin\alpha$$
$$C_t = \pi C_f \cos\alpha \qquad (6)$$

Eames (1968) proposed a refinement of this hypothesis for faired cable and includes a "form" drag term opposite to the direction of motion and proportional to sin α. The expressions then take the form

$$C_n = C_{n90}\,(1-m)\,\sin^2\alpha + C_{n90}\,m\,\sin\alpha$$
$$C_t = C_{n90}\,(m + n\,\sin\alpha)\,\cos\alpha \qquad (7)$$

where m is called the "friction ratio" (ie $\pi\, C_f/C_{n90}$) and n the "form ratio." The C_n' expression is of the same form as that of Hoerner (1965) but has the added advantage that, at $\alpha = 90^o$, $C_n' = C_{n90}$ precisely. The value of $(1-m)$ is of the order of 0.98.

Eames (1968) suggested that although his form ratio concept has no obvious physical meaning the term reduces the value of C_t at low angles to take account of the apparent increase in wire thickness.

Figure 9 shows the experimental data of Relf and Powell (1917), Chubarov (1962), Nomura and Nozawa (1955) and Matrosov (1961) for 6 stranded wire. The scatter of the data may be due to the different construction of the specimens. Stengel (1968) concluded that a relatively small and constant value of 0.006 was appropriate. The data of Relf and Powell, Matrosov and Nomura and Nozawa are not inconsistent with Eames expression (7). Chubarov did not take measurements in the important region between $\alpha = 0$ and 30 degrees. He did, however, test wires with different numbers of strands. The values of C_t for 3, 6, 18 and 20 strands show no systematic variation with number of strands (Fig. 10).

Figure 9 shows lines representing Eames function for a range of values of form ratio and a friction ratio of 0.03.

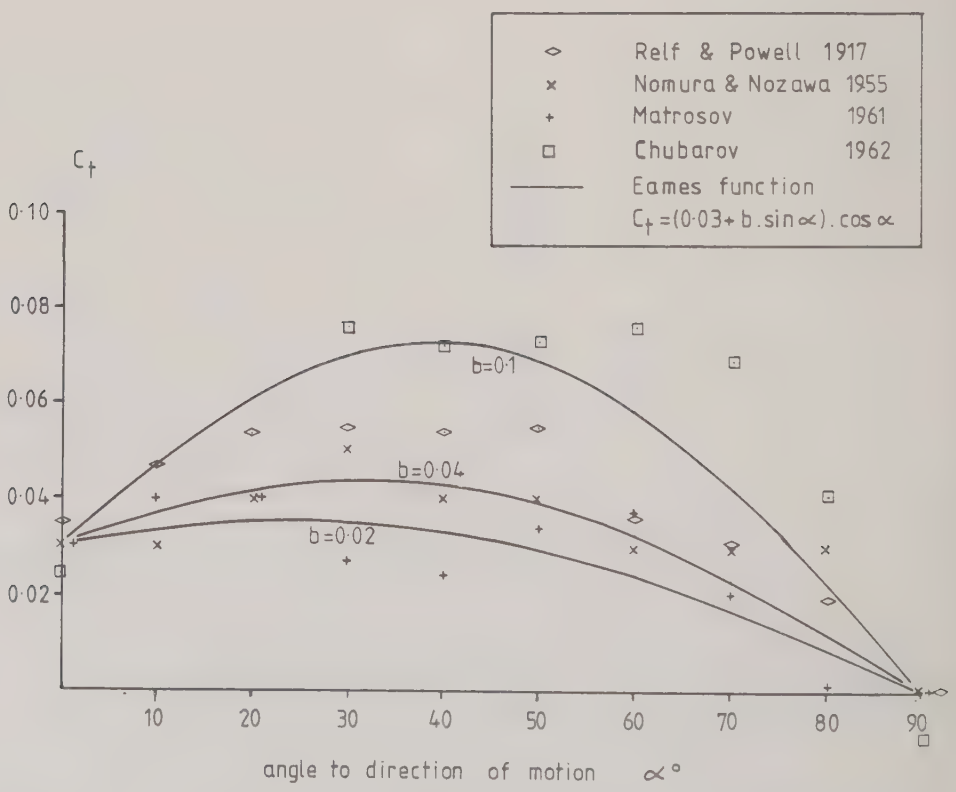


Figure 9. The variation of tangential force coefficient for 6 stranded wires with angle to the direction of motion and comparison with theory

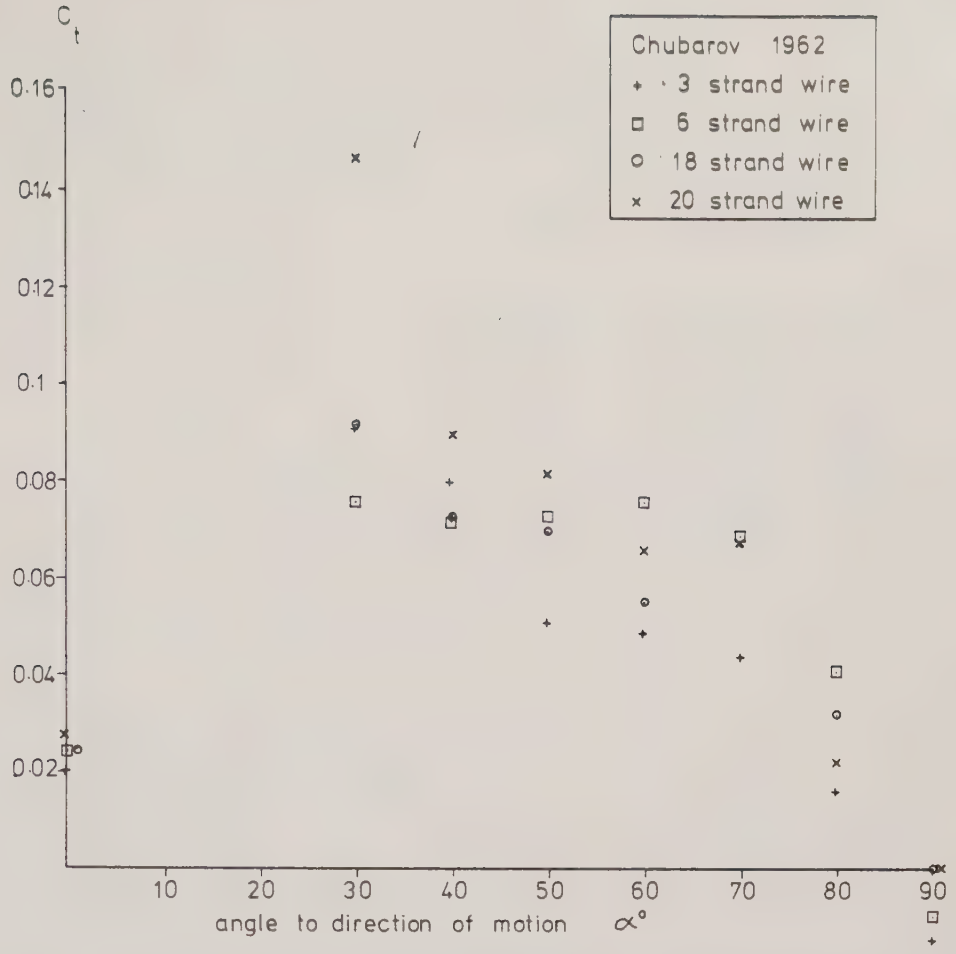


Figure 10. The variation of tangential force coefficient with angle to the direction of motion for wires with different numbers of strands round the circumference

Lastly, the sea trials data of Alekseev (1964), MacLennan (1979, 1980) and Starovoitov and Nikeshin (1975) are plotted in Figure 11. It is generally accepted that the friction coefficient C_f reduces as Reynolds Number increases (Hoerner, 1965). In these tests the angle α reduces as speed and hence Reynolds Number increase. Thus, at low α, mC_{n90} ($=\pi C_f$) will be low, and at high α, this term will be higher. It was noted above that vibration is likely to increase as speed reduces in these experiments. Therefore, as α increases, the vibration amplitude and hence the effective wire thickness will increase or at least will not decrease as fast as the increase in α implies. Thus, it might be expected that the value of the form ratio term $n\,C_{n90}$, increases with α.

This hypothesis may explain not only the low values of C_t at low α but also the steeper slope of the variation of C_t with α. It should be emphasised that when towing trawl gear these conditions may no longer prevail.

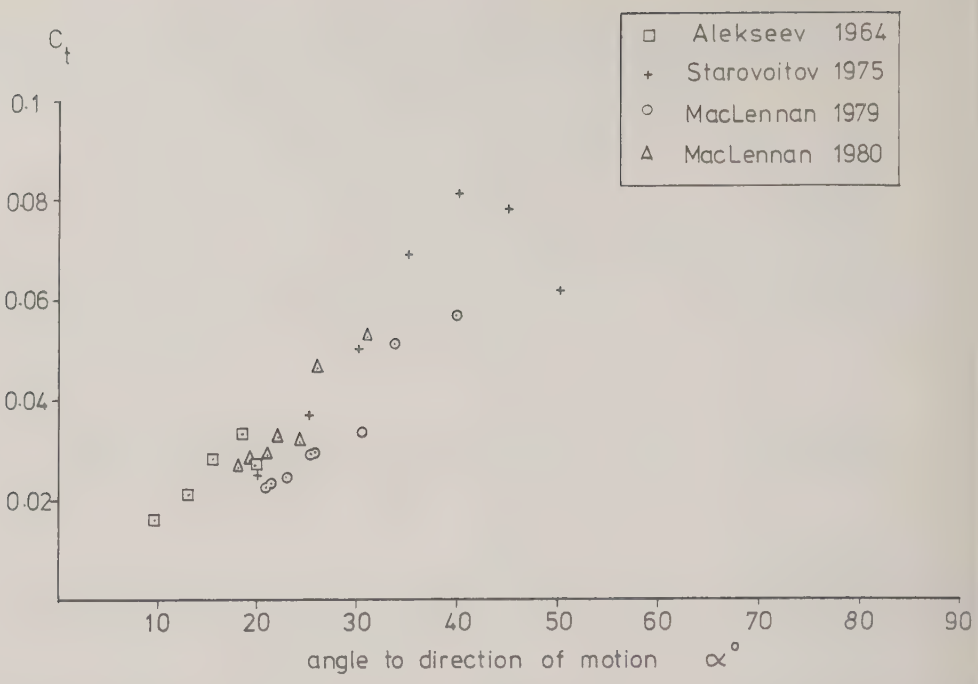


Figure 11. The variation of tangential force coefficient for streamed stranded wires with angle to the direction of motion, from sea trials data

Side force coefficient C_s

If a smooth cylinder is lying in the xy plane the hydrodynamic forces acting on the cylinder are r_n and r_t only (Fig. 5). However, a warp differs from a cylinder owing to its laid or twisted construction. Owing to the asymmetry of the strands the flow on each side of the warp is different, so the velocity and pressure fields are not symmetrical round the warp section. A side force r_s exists, defined as

$$r_s = C_s \tfrac{1}{2} \rho v^2 d \text{ per unit length}$$

Experimental data for C_s from various sources are plotted in Figure 12 for 6 stranded wire.

Stengel (1968) obtained wind tunnel data using large wire models of diameter 187 mm. The data for the side force coefficient for the models were fitted to the formula

$$C_s = 1.44\ (3.32 \times 10^{-3} + 1.62 \times 10^{-5} \alpha) \text{ for } 0 < \alpha < 45^o$$

where a correction factor of 1.44 was required. This factor was determined from the difference in level of the drag coefficient C_x for the large model and real warps (diameters 14 mm to 26 mm) and was considered to be due to the low aspect ratio of 12 of the model. Furthermore, the large model was not identical to the real warps in construction since the individual wires making up each of the six strands were not twisted but lay parallel to the axis of the strand. This difference may particularly affect the circulation round the wire and hence the level of C_s.

Matrosov (1961) obtained results which show rather low values for C_s. Lebedev (1968) determined the side force coefficient during sea trials for a range of attack angles from 20^o to 40^o.

Gabriuk and Gabriuk (1974) tested 21.5 mm wire in a wind tunnel at $R_d = 2 \times 10^4$. The results suggested a somewhat higher circulation at all attack angles up to 60^o.

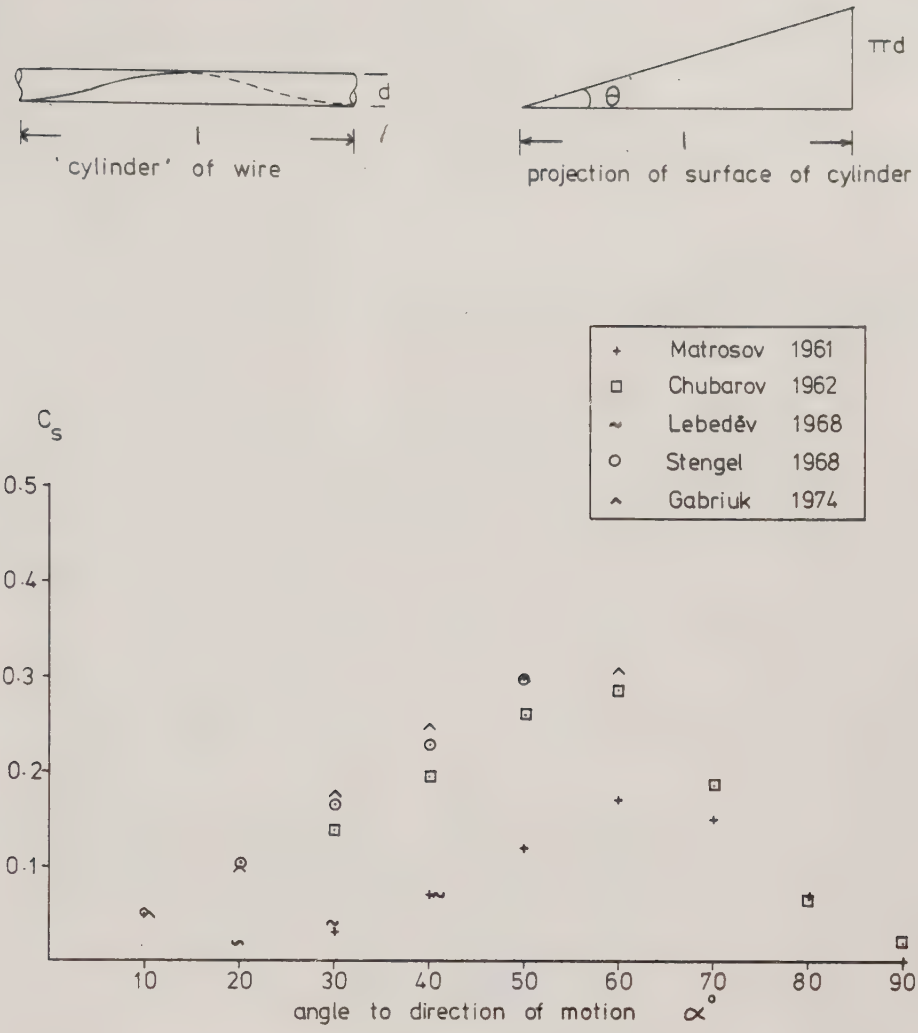


Figure 12. The variation of side force coefficient for stranded wires with angle to the direction of motion, from wind tunnel and water tank test data

Chubarov (1962) made measurements of C_s in a wind tunnel using wires of different construction (3, 6 and 18 strand), having found that a 20 stranded wire had no measurable side force. The value of C_s reached a maximum between 50° and 70° for all types of wire. Chubarov did not measure C_s in the practically important range of α between 0° and 30°. The results are shown in Figure 13.

Crewe (1961, 1964) analysed the problem theoretically using circulation theory. The side force per unit length is given by

$$r_s = \rho v \Gamma \sin\alpha \qquad (8)$$

where Γ is the circulation given by the integral of the fluid velocity around a path enclosing the body.

To determine Γ, Crewe argued that if the lay completely deflected the component of velocity parallel to the wire ($v \cos\alpha$) then it would give a rotational component of velocity adjacent to the wire surface of, say $v \cos\alpha \tan\lambda$ where λ is a mean lay angle. However, the flow distant from the surface will not be deflected so that in practice an effective value at the surface might be

$$fv \cos\alpha \tan\lambda$$

where f is to be determined.

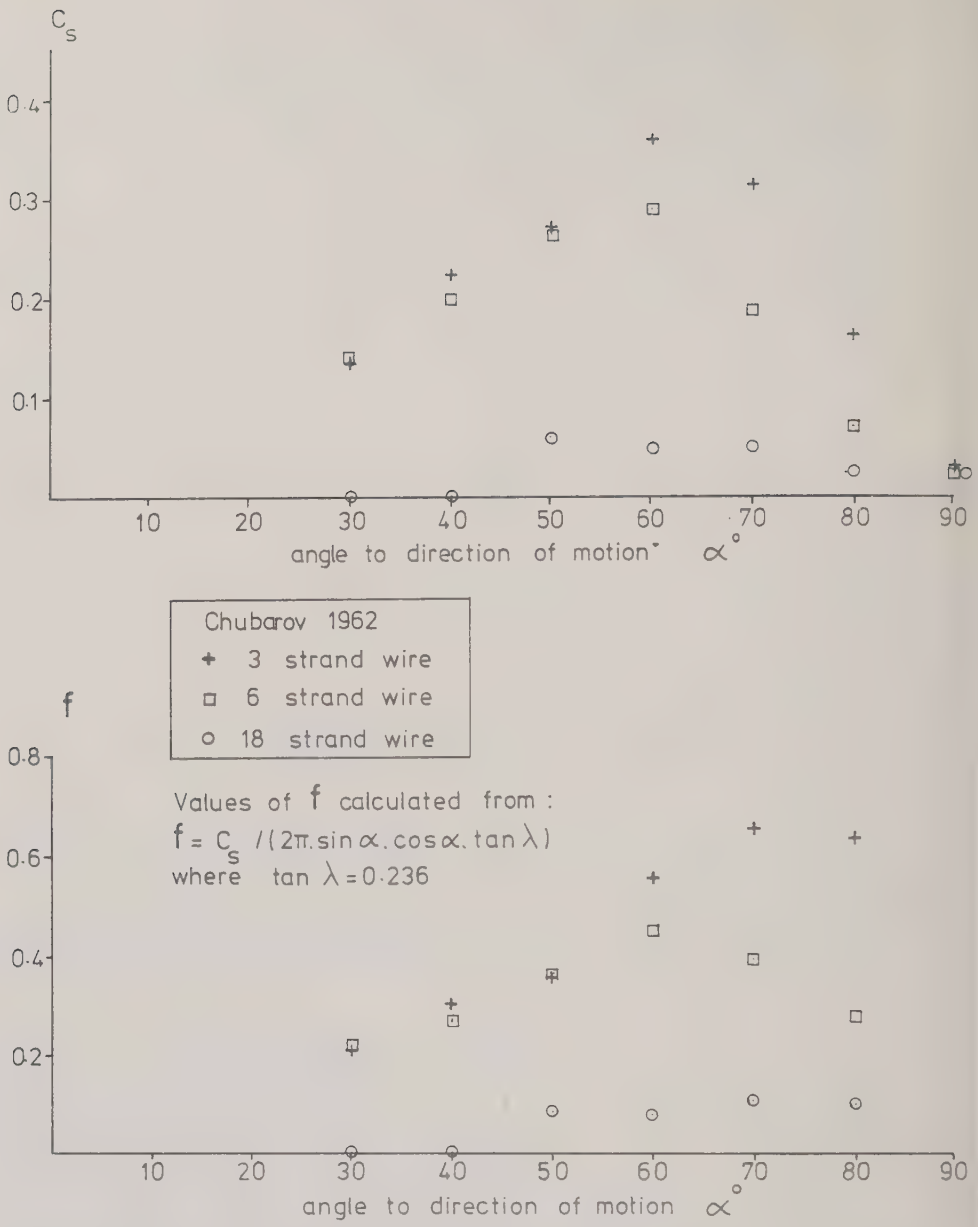


Figure 13. The variation of side force coefficient and "slip" factor with angle to the direction of motion for wires with different numbers of strands round the circumference

The integral round the surface then becomes

$$\Gamma = fv \cos\alpha \tan\lambda \oint ds \qquad (9)$$

where $\oint ds$ is the circumference of the wire, πd, appropriate to the rotation component of velocity at the wire surface. From equation (8) we have

$$r_s = \pi f d \rho v^2 \sin\alpha \cos\alpha \tan\lambda$$

or, from equation (4),

$$C_s = 2\pi f \sin\alpha \cos\alpha \tan\lambda \qquad (10)$$

It is now necessary to determine λ. Because the strands are laid in the opposite sense to the individual filaments in each strand for wires with regular lay then the mean lay angle might be taken as $\lambda = \theta/2$ where θ is the pitch angle and $\tan\theta = \pi d/l$ (see diagram in Fig. 12).

For wires with Langs lay where the strands are twisted in the same direction as the filaments in the strands then the mean lay angle might be $\lambda = 3\theta/2$, and

for Stengel's large wire model (1968) the mean lay angle might be taken as $\lambda = \theta$ since the filaments lie parallel to the strands.

Gabriuk and Gabriuk (1974) mentioned that the wire used in the Soviet Union has ratio l/d in the range from 7 to 7.5 which corresponds to values of tan θ from 0.45 to 0.42.

A range of sizes of wire rope from 4 mm to 26 mm was measured at the Marine Laboratory, Aberdeen, and the mean value of tan θ was found to be 0.50 with a standard deviation of 0.037. There was no clear variation with size.

Lastly we need to evaluate f. Following D Gerry, Crewe (1961) took $f = 1 - \cos\alpha$, arguing that "when the strength of flow parallel to the rope is great the deflection due to the lay will be small, and vice versa, as may be physically reasonable, the $1 - \cos\alpha$ being a "slip factor".

Values of f have been plotted in Figure 14 using, from equation (10),

$$f = C_S / (2\pi \sin\alpha \cos\alpha \tan\lambda)$$

where tan λ = tan θ for Stengel's large wire model and tan λ = tan $\theta/2$ for all other data.

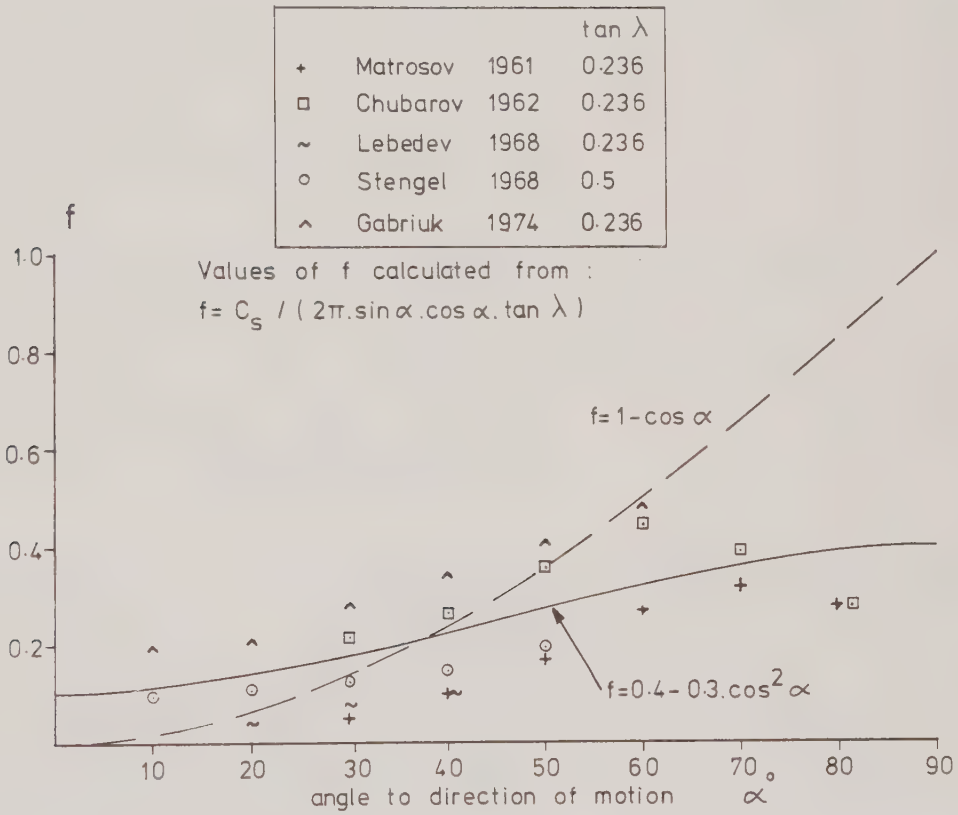


Figure 14. The variation of side force "slip" factor with angle to the direction of motion, from wind tunnel and water tank test data

There is a suggestion that at $\alpha = 0$, f is not zero which is plausible even though C_S is zero, and also that the curve may flatten out at high α, or even reduce towards zero. Certainly the function $1 - \cos\alpha$ is not supported by this evidence.

A regression of the data in Figure 14 suggests for 6 stranded wire

$$f = 0.4 - 0.3 \cos^2\alpha \qquad (11)$$

The factor f is dependent on the orientation and profile of the axial velocity component, possibly in a similar way to the tangential force coefficient, C_t. There is, indeed, a similarity between their variations with α which further data may confirm.

From Figure 13 it can be seen that the empirical function (11) does not adequately describe the situation for wires with different numbers of strands. As expected for 3 stranded wire the values of f are larger at high α and for 18 stranded wire f is much lower at all α.

Suggested Values of Force Coefficients

From the evidence presented and discussed above we suggest in this section the formulae and basic coefficient values to be used for the calculation of 6 stranded wire shape.

Normal force coefficient

The variation of normal force coefficient with attack angle for non-vibrating wires is adequately represented by the formula

$$C_n' = C_{n90} (1-m) \sin^2\alpha + C_{n90}\, m \sin\alpha$$

or

$$C_n = C_{n90} (1-m) + C_{n90}\, m/\sin\alpha$$

where C_{n90} is the normal force coefficient when the flow is perpendicular to the wire and m is the friction ratio, ie $\pi C_f/C_{n90}$, if C_f is the skin friction coefficient based on surface area.

It was shown above (p 6 *et seq.*) that C_{n90} increases with decrease in Reynolds Number, with increase in number of strands and with increase in vibration. However, further evidence is required to quantify these relationships.

If it is assumed during wind tunnel tests that wire vibration is not significant, then a value of C_{n90} for non-vibrating 6 stranded wire can be taken as 1.1 over the range of Reynolds Numbers from 8×10^3 to 6×10^4.

Until more systematic tests are done on vibration of long wires under tension it will be necessary to assume a factor for vibration under trawling conditions. A value of 1.35 has been chosen giving C_{n90} of, say, 1.5 for a typical vibrating trawl wire.

Tangential force coefficient

The expression for C_t given in (7) is more representative of the behaviour shown in Figures 9, 10 and 11 than the expression of (6).

We therefore take

$$C_t = C_{n90} (m + n \sin\alpha) \cos\alpha$$

There is reasonable agreement from wind tunnel and tank tests (Fig. 9) that at $\alpha = 0$, C_t is of the order 0.02 to 0.04, although it would be expected to vary with the coefficient of twist of the wire, the number of strands, the Reynolds Number and the vibration.

We will take

$$m\, C_{n90} = 0.03 \text{ and } n\, C_{n90} = 0.06$$

appropriate to non-vibrating wires ($C_{n90} = 1.1$).

Tentatively we can then say

$$m = 0.027 \text{ and } n = 0.055 \text{ for typical trawl wires}$$

If we assume typical vibrating trawl wires have $C_{n90} = 1.5$ but unchanged values of m and n,

$$m\,C_{n90} = 0.041 \text{ and } n\,C_{n90} = 0.082$$

Side force coefficient

Crewe's circulation theory (1961) gives a variation of C_s with α (equation 10) which fits the limited evidence well.

The mean lay angle term, tan λ, and the "slip" factor, f, require further experimental data.

In the absence of such evidence we suggest for 6 stranded regular lay wire

$$f = 0.4 - 0.3\cos^2\alpha$$

and $\tan\lambda = \tan(\theta/2)$ where $\tan\theta = 0.5$ for 6 stranded wire.

Hence $C_s = 1.48 \sin\alpha \cos\alpha (0.4 - 0.3\cos^2\alpha)$

The sign of the side force should be chosen carefully with reference to the table below. The sign varies for single boat trawling compared with pair trawling, for port and starboard wires, and for left and right hand lay wires.

	PORT WARP		STARBOARD WARP	
	Left Hand Lay S twist	Right Hand Lay Z twist	Left Hand Lay S twist	Right Hand Lay Z twist
Single boat	–	+	+	–
Pair	+	–	–	+

Weight of 6 Stranded Wire in Water

Manufacturer's data for a range of sizes of warp have been used to derive simple formulae for the calculation of wire weight in air and water.

Regression lines through these data give the following equations:

$$w_1 = 0.0039\,d^2$$
$$w = 0.00305\,d^2$$

where

w_1 is weight of wire in air per unit length (kg m^{-1})

w is weight of wire in water per unit length (kg m^{-1})

d is measured diameter of the wire (mm)

We suggest the weight of 6 stranded wire is calculated using the above formulae.

Summary

The basic equations for the forces acting on a flexible inextensible wire towed steadily through water are given.

Data on hydrodynamic coefficients for stranded wires are presented. New forms for the variation with angle to the flow of the normal, tangential and side force coefficients are proposed for 6 stranded trawl wire.

Experiments to determine hydrodynamic coefficients in which a warp is towed alone or with only a weight at its lower end may not give values appropriate for use in trawling applications.

Simple formulae for weight in air and water of 6 stranded wire are given.

Data for wires of different numbers of strands are presented and discussed.

There is a need for more careful experiments to verify or improve these coefficient forms and, in particular, to determine the effect of vibration, Reynolds Number variation, numbers of strands and coefficient of twist.

Acknowledgements

Much of the original thought on the basic hydrodynamic theory of wires is due to the late Peter Crewe of the British Hovercraft Corporation. It was published in a series of reports written under contract to the White Fish Authority, British Trawler Federation, and Marine Laboratory, Aberdeen, over the period from 1959 to 1981. This report relies heavily on Crewe's contribution, particularly in the areas of wire vibration and the theory of the side force due to the stranded nature of the wire.

We would also like to acknowledge the help given by D N MacLennan and members of the Gear and Instrumentation Sections of the Marine Laboratory.

We have relied also on the published data of scientists in many countries and would like to acknowledge their contribution.

References

Alekseev, N.I. 1964. [Determination of the hydrodynamic characteristics of the warp at sea.] *Rybnoe khozyaistvo Moskva,* **40**(1), 56-58. (In Russian)

Chubarov, S.N. 1962. [The effect of hydrodynamic forces on wires and the choice of wire for high speed and deep-sea trawling.] *Rybnoe khozyaistvo Moskva,* **38** (5), 45-49. (In Russian)

Crewe, P.R. 1961. Trawl warps — further theory including preliminary survey of vibration behaviour. Westland Aircraft Ltd. (Saunders-Roe Division). Report H/0/155. Produced under contract to the White Fish Authority and British Trawler Federation, 70pp.

Crewe, P.R. 1964. A theory of the "Aeolian" and "galloping" vibrations of cylindrical structures with particular reference to trawl warps. Westland Aircraft Ltd. (Saunders-Roe Division). Report H/0/185. Produced under contract to the White Fish Authority, 69pp.

Eames, M.C. 1968. Steady state theory of towing cables. *Transactions of the Royal Institution of Naval Architects,* **110**, 185-206.

Every, M.J. 1981. A brief survey of the steady drag data available for application to unfaired umbilical cables. British Hydromechanics Research Association Report RR1715, 40pp.

Ferro, R.S.T. 1981. The specification of the dimensions of twisted wire or twine as a basis for selecting hydrodynamic force coefficients. *Marine Laboratory Working Paper* (81/13), 8pp.

Gabriuk, L.V. and Gabriuk, V.I. 1974. [Experimental determination of the side force on steel and capron cables.] *Rybnoe khozyaistvo Moskva,* **50** (2), 44-46. (In Russian)

Griffin, O.M., Kandiver, J.K., Skop, R.A. and Meggit, D.J. 1982. The strumming vibrations of marine cables. *Ocean Science and Engineering,* **7** (4), 461-498.

Hoerner, S.F. 1965. Fluid-dynamic drag. Published by the author.

Lebedev, E.A. 1968. [On left and right hand laid wires.] *Rybnoe khozyaistvo Moskva,* **44** (7), 40-42. (In Russian)

References (Contd.)

MacLennan, D.N. 1979. Hydrodynamic characteristics of trawl warps. *Scottish Fisheries Research Report* (16), 10pp.

MacLennan, D.N. 1980. Further hydrodynamic force measurements on trawl warps. *Marine Laboratory/Working Paper* (80/5), 8pp.

Matrosov, I.R. 1961. [Theoretical basis for calculating the movement of vessel and trawl.] *Rybnoe khozyaistvo Moskva,* **37**(6), 41-53. (In Russian)

Nomura, M. and Nozawa, Y. 1955. [On the inclination of a twine in a current.] *Bulletin of the Japanese Society of Scientific Fisheries,* **20**, 762. (In Japanese)

Relf, E.F. and Powell, C.H. 1917. Tests on smooth and stranded wires inclined to the wind direction, and a comparison of results on stranded wires in air and water. *Aeronautical Research Council, Reports and Memoranda (New Series),* No. 307, January 1917, 7pp.

Skop, R.A., Griffin, O.M. and Ramberg, S.E. 1976. Seacon II. Strumming prediction. U.S. Naval Research Laboratory, Washington D.C. *NRL Memorandum Report 3383.*

Starovoitov, P.A. and Nikeshin, K.N. 1975. [Determination of the hydrodynamic characteristics of a towed cable.] *Rybnoe khozyaistvo Moskva,* **51** (5), 43-46. (In Russian)

Stengel, H. 1968. Verfahren zur Berechnung der Kurrleinenform und -spannung. *Fischerei-Forschung,* **6** (3), 73-94.

Notation

C_f	skin friction force coefficient based on surface area π d ds
C_n	normal force coefficient based on projected area d ds
C_n'	$C_n \sin^2 \alpha$
C_{n90}	normal force coefficient of warp perpendicular to flow based on projected area d ds
C_s	side force coefficient based on projected area d ds
C_t	tangential force coefficient based on projected area d ds
C_x, C_y	force coefficients along x and y axes based on projected area d ds
d	diameter of wire
ds	wire element length
dT	change in tension along wire element
f	slip factor = $0.4 - 0.3 \cos^2 \alpha$ for rotational velocity round wire due to strands
k	coefficient $\frac{1}{2} \rho v^2 d$
l	pitch of the twist of the wire
m	friction ratio (see p 10)
n	form ratio (see p 10)
suffices n, t, s	components of parameter in directions normal and tangential to the wire and in a direction perpendicular to both, respectively
R_d	Reynolds Number based on diameter = vd/ν
r	hydrodynamic force per unit length

T	wire tension
v	speed of water relative to wire
w	weight of wire in water per unit length
w_1	weight of wire in air per unit length
x, y, z	coordinates of point on wire (see Fig. 2)
suffices x, y, z	components of parameter along x, y, z axes, respectively
α, β, γ	the angles of the wire element to the x, y and z axes respectively
Γ	circulation (see p 13)
θ	pitch angle of wire twist, tan θ = d/l (see Fig. 13)
λ	mean lay angle (see p 13)
ρ	density of water
ν	coefficient of kinematic viscosity for water

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